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The Turbulent Generation of Outward Traveling Alfvénic Fluctuations in the Solar Wind

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THE TURBULENT GENERATION OF OUTWARD TRAVELING ALFVÉNIC FLUCTUATIONS

IN THE SOLAR WIND

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Abstract

From an analysis of magnetohydrodymic turbulent processes, we conclude that the frequent observation of outward propagating Alfvénic fluctuations in the solar wind can arise from early stages of _in situ_ turbulent evolution, and need not reflect coronal processes as has hitherto been assumed.

Spacecraft observations have indicated that in the interplanetary medium a high degree of correlation frequently exists between the fluctuating magnetic field $\vec{b}$ and the fluctuating plasma fluid velocity $\vec{v}$. These are "Alfvénic fluctuations" with rms fluctuation levels comparable to the mean magnetic field and have nearly aligned $\vec{v}$ and $\vec{b}$.[1,2] Finite amplitude Alfvénic fluctuations (with $\vec{v} = \pm\vec{b}$, $\vec{b}$ measured in units of an Alfvén speed) are exact solutions to the equations of ideal incompressible magnetohydrodynamics (MHD) turbulence[3] and are candidates for preferred final states of MHD[4].

Though the evolution of MHD turbulence is complex, it can proceed toward final states which can be simply described. It has been recently argued[5] that MHD turbulence can increase the degree of alignment at large times and that this process produces interplanetary Alfvénic fluctuations. Evidence in support of "dynamic alignment" has accumulated in the form of closure calculations[6] and from numerical solutions of the MHD equations.[7,8] Under other conditions, evidence has been presented [8,9,10] that MHD turbulence will instead evolve toward a minimum-energy state, with a decaying ratio of kinetic to magnetic energy. It is not entirely clear what boundaries separate these two regimes and this remains an unresolved issue in MHD turbulence theory.[8]

Here we present further evidence for dynamic alignment of $\vec{v}$ and $\vec{b}$ in two-dimensional MHD turbulence from which we see that interplanetary fluctuations need not represent time asymptotic states. Rather, we argue that interplanetary Alfvénic fluctuations are generated in situ in the early stage of dynamic alignment. Our model not only provides an explimation for inertial range alignment of $\vec{v}$ and $\vec{b}$ in the solar wind, but also accounts for the fact that the sign of this correlation (relative to the direction of the mean magnetic field) corresponds to the observed "direction of propagation": away from the sun[2]. We find support for the viewpoint that MHD fluctuations in the

solar wind resemble turbulence[11,12] arising from local stirring of the medium.

There are at least two important questions involved in the generation of Alfvénic states: First, does dynamic alignment occur and why? Second, if a high degree of alignment initially exists, does it inhibit further development of turbulent processes, such as spectral transfer? (Perfectly aligned states exhibit no spectral transfer, which has been used to suggest[13] that interplanetary fluctuations are not, properly speaking, evolving turbulence.)

We have investigated these questions numerically using an incompressible MHD spectral method code[9,14]. The equations solved are, in a familiar dimensionless form:

$$\partial \vec{v}/\partial t + \vec{v}\cdot\nabla\vec{v} = -\nabla p + \vec{b}\cdot\nabla\vec{b} + \nu\nabla^2\vec{v} \qquad (1)$$

$$\partial \vec{b}/\partial t + \vec{v}\cdot\nabla\vec{b} = \vec{b}\cdot\nabla\vec{v} + \mu\nabla^2\vec{b}. \qquad (2)$$

p is the mechanical plus magnetic pressure and $\nabla\cdot\vec{v} = 0 = \nabla\cdot\vec{b}$. The magnetic and mechanical Reynolds numbers are $1/\mu$ and $1/\nu$, respectively. Periodic boundary conditions in the x-y plane are assumed and $\partial/\partial z \equiv 0$. The Fourier coefficients $\vec{v}(\vec{k},t)$ and $\vec{b}(\vec{k},t)$ are advanced from initial (t=0) values, for each wave number $\vec{k}$, by integrating the truncated Fourier transformed versions of (1) and (2). Time is scaled to the Alfvén transit time of unit distance corresponding to the initial magnetic field.

The degree of alignment is measured by the ratio of two ideal "rugged" invariants, the cross helicity, $H_c = \langle\vec{v}\cdot\vec{b}\rangle/2$ and the energy $E = \langle v^2 + b^2\rangle/2$ (brackets denote a spatial average). Extremal values of H_c/E ($\pm 1/2$) indicate perfect alignment.

Four simulations are discussed here, designated A, B, C and D. Runs A, B,

and C were obtained with a 128×128 code with Reynolds numbers of 400. Included ed wavevectors have integer components ranging from 1 to 64 and their negative counterparts. At t=0, all non-vanishing Fourier amplitudes were confined to a circular annulus $9 \leq k^2 \leq 25$ and had a fixed kinetic energy, twice as much magnetic energy, and phases chosen as follows: The phase of $\vec{b}(\vec{k},0)$ was chosen randomly and a phase angle θ was chosen between $\vec{v}(\vec{k},0)$ and $\vec{b}(\vec{k},0)$. This specifies the modal cross helicity, $H_c(\vec{k}) = Re\ \vec{v}*(\vec{k})\cdot\vec{b}(\vec{k})$. Run A is initially highly aligned with arccos(0.95) = θ and H_c/E = 0.45. Run B is only moderately aligned with arccos(.3) = θ and H_c/E = 0.14. Run C has the phases of $\vec{b}$ and $\vec{v}$ both randomly chosen so that $H_c \approx 0$. Initially run D (64×64 grid; Reynolds numbers 400) consisted of the homogeneous turbulence used in A, B, and C superimposed on a large scale shear flow and a correlated large scale $\vec{b}$. At t=0, H_c/E= -0.4. Time steps were either 1/256 or 1/512. Other runs, not described here, displayed similar results.

Direction averaged modal energy spectra for runs A and C are shown in Fig. 1, both at t=0.19. Initial energy spectra in both runs were identical. Spectral transfer out of the initially excited annulus is not noticeably inhibited by the high degree of alignment in run A relative to what it is in run C. The nearly power-law inertial range in run A occurs at a lower level than for the $H_c \approx 0$ case C, indicating that initial alignment can at most slow transfer, but cannot prevent turbulence from occurring.

Fig. 2 illustrates the temporal development of dynamic alignment. The ratio $|H_c/E|$ for runs A and B increases nearly monotonically, in agreement with previously reported results.[6,7,8]

A physical explanation for dynamic alignment is suggested by rewriting (1) and (2) in the Elsässer variables $\vec{z}^{\pm} = \vec{v} \pm \vec{b}$. We focus on the low-k region, neglecting dissipative terms and combine eqs. (1) and (2) into $\partial\vec{z}^{\pm}/\partial t =$

$-\vec{z}^{\pm}\cdot\nabla\vec{z}^{\pm} - \nabla p$. p is determined by using $\nabla\cdot\vec{z}^{\pm} = 0$ to yield a Poisson equation.

Consider now the case $|\vec{z}^+| \gg |\vec{z}^-|$. Note that $\vec{z}^+$ is nearly independent of time. Since ∇p is of order $\vec{z}^-\cdot\nabla\vec{z}^+$, the fractional rate $|\partial\vec{z}^+/\partial t|/|\vec{z}^+|$ goes to zero as $\vec{z}^- \to 0$. However, the fractional rate $|\partial\vec{z}^-/\partial t|/|\vec{z}^-|$ remains of $O(1)$ as $\vec{z}^- \to 0$. The spectrum of $\vec{z}^+$ is effectively frozen, but that of $\vec{z}^-$ continues to evolve and to acquire higher wave number components. In fact, at every time step the $\vec{z}^-$ spectrum will spread to all additive combinations of wave numbers that comprised those present in $\vec{z}^+(0)$ and $\vec{z}^-$ at the previous time step. The transfer of the $\vec{z}^-$ spectrum to higher wave numbers will continue at a fractional rate that remains finite even as $\vec{z}^-$ becomes small. Eventually, $\vec{z}^-$ will be dissipated as it reaches the higher k values, enhancing the inequality $|\vec{z}^+| \gg |\vec{z}^-|$. We believe this mechanism, by which the majority species cannibalizes the minority one by sending it to high wave numbers to be dissipated, is the essential mechanism involved in dynamic alignment.

The simulations reflect this qualitative behavior: Fig. 3 shows the normalized direction-averaged cross helicity spectrum $2H_c(k)/E(k)$ vs. k at an early stage of runs A, B and D. The transfer of excitation to k's higher than those initially present consists almost entirely of cross helicity contributions of opposite sign to those in the energy-containing low-k part of the spectrum. For runs A and B, $\vec{z}^-$ is transferred to toward the dissipation range, as is $\vec{z}^+$ for run D.

This effect apparently dominates for times of the order of an Alfvén transit time or an "eddy turnover time." Subsequently, the simulations indicate that the normalized cross helicity spectra undergo a further systematic evolution as illustrated for run A in Fig. 4. The inertial range gradually loses its one-signed character as the majority species slowly moves out of the low k's. For highly correlated runs (such as A), minority species

domination of the highest computed k's persists for very long times (beyond $t=20$, not shown).

In runs with less aligned initial correlation such as B, behavior similar to that of in Fig. 4 is observed, but with less pronounced minority species domination of high k's (not shown). The high k part of the spectrum can become more or less equally populated with z^+ and z^-. Because z^+ and z^- have equal dissipation rates, dynamic alignment continues, leaving an excess of majority species in the energy containing scales. In no case have we seen broad-band domination of the inertial range by the majority species before very long times (> 20). However, the early time appearance of an inertial range populated by the minority species and the very slow spread of the majority species from energy containing to higher k are features common to all our simulations.

These results suggest a model for the turbulent production of interplanetary Alfvénic fluctuations. Consider a volume of solar wind plasma containing a mean magnetic field lying entirely in a single magnetic sector.[15] The large scale velocity field is radially outward, so that the sign of the radial component of the mean magnetic field determines the sign of the large scale contribution to $H_c = H_c(\text{large})$. $H_c(\text{large})$ is generally nonzero in the vicinity of high speed streams (where Alfvénic fluctuations are usually observed) even in the reference frame moving with the mean solar wind velocity. Now assume that inertial range fluctuations are due, at least in part, to nonlinear couplings which drain energy in the large scale fields and pump the small scale fluctuations. If the energy transfer produces dynamic alignment consistent with the results described above, then at "early times" the inertial range of interplanetary fluctuations would contain a sign of cross helicity opposite to that present in the large scale energy containing

structures; i.e., the cross helicity of the inertial range fluctuations, say H_c(inertial), would have a sign corresponding to outward propagation.

This model is consistent with spectral analysis of highly Alfvénic periods which often shows that long wavelength fluctuations have $H_c(k)$ opposite in sign to the inertial range fluctuations.[11] These "inward propagating" long wavelength waves would be the transition in the spectrum between the large scale energy containing structures which are driving the turbulence and the inertial range fluctuations which are being driven.

During the later stage, as the turbulence gets "older", the inertial range may become equally populated with both z^+ and z^- as envisioned in Ref. 5. One might anticipate that interplanetary plasma which has spent a longer time being "stirred" is less likely to be Alfvénic. One reported observation at 5 AU behind a high speed stream is possible evidence of this. In that spectrum, the cross helicity in the inertial range oscillated in sign and was generally not close to its maximal values (Ref. 11, Fig. 11), indicating weak inward and outward propagating Alfvénic fluctuations.

Another possibility,[5] is that dynamic alignment enhances a seed correlation of $\vec{v}$ and $\vec{b}$ so that by 1 AU highly Alfvénic fluctuations would be seen. In contrast to our model, the majority $\vec{z}$-field would represent the Alfvénic fluctuations. One difficulty with this model is the limited time available for turbulent evolution as the solar wind flows between the sun and 1 AU. A substantial fractional increase of the $\vec{v}$-$\vec{b}$ correlation requires tens of Alfvén transit times (cf. Fig. 2). For nominal interplanetary conditions at 1 AU, the energy containing scale is approximately 10^{12} cm [11,16] and the Alfvén speed is approximately one tenth the flow speed of about 4×10^7 cm/s. Thus only a few Alfvén transit times elapse for each AU of mean plasma motion and it is unlikely that there is time for a substantial degree of dynamic

alignment to occur by 1 AU. Furthermore, an additional mechanism would be required to account for the outward traveling sense of the $\vec{v}-\vec{b}$ correlation.

Our model naturally generates outward propagating fluctuations. The early stages of MHD turbulence produce an inertial range with fluctuating velocity-magnetic field correlation opposite in sign to the correlation of the large scale velocity and magnetic fields which drive the turbulence. This can account for the widespread occurrence of Alfvénic fluctuations in the solar wind. The analytical model presented is essentially unchanged by the addition of a mean magnetic field and is applicable to any dimensionality. Simulations in two dimensions have shown the mechanism to act starting from a variety of initial conditions.

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Figure Captions

Figure 1. Modal total energy spectra at t ≈ 0.19 for runs C (uncorrelated initial fields) and A (highly correlated initial fields). The inital spectra were identical except for the values of $H_c(k)$. Spectral transfer occurs in both cases.

Figure 2. The ratio H_c/E vs. time for runs A and B, showing the near monotone increase in the degree of alignment of $\vec{v}$ and $\vec{b}$ due to turbulence.

Figure 3. Normalized cross helicity spectrum for runs A and B at t = 0.19 and D at t ≈ 0.4. Data in Figs. 3 and 4 were smoothed by a 9 point moving average before plotting. In all three cases, the transfer of cross helicity to high k is almost exclusively opposite in sign to that of the low k t=0 state.

Figure 4. (a) Run A at t ≈ 0.98 when transfer of the initially dominant z^+-mode into the inertial range begins resulting in a $H_c(k)$ mixed in sign. (b) Run A in a later stage (t = 7.8) where the z^+ field dominates the cross helicity spectrum except at the highest k's.

Figure 1

Figure 2

Figure 3

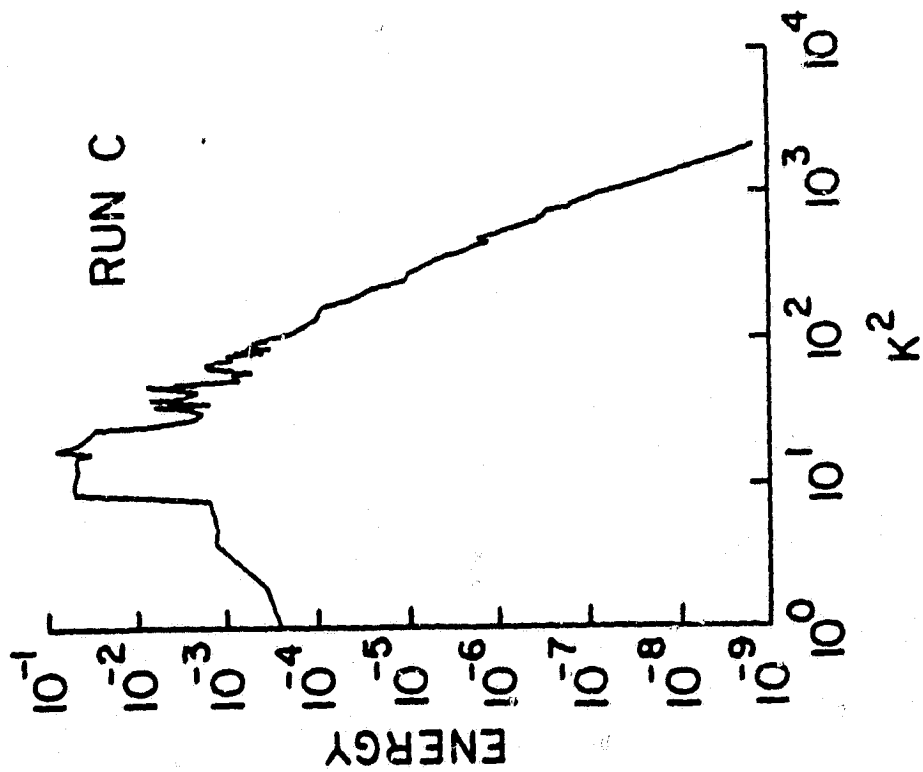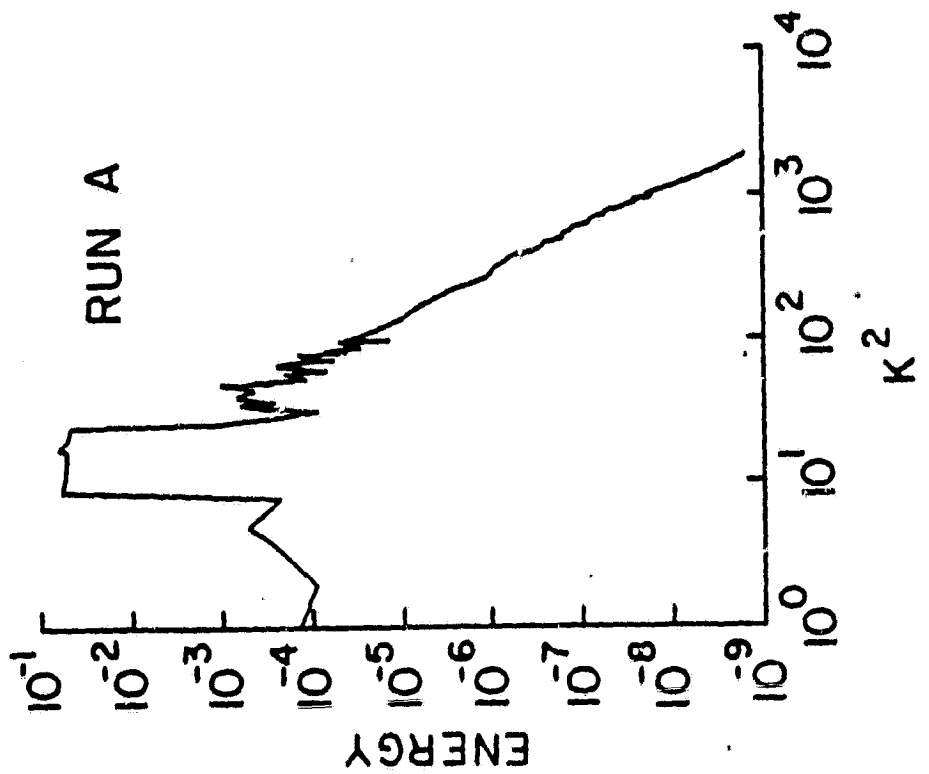Figure 4